

Abundances of light elements in metal-poor stars. I.

Atmospheric parameters and a new T_{eff} scale

R.G. Gratton¹, E. Carretta^{2,3}, F. Castelli⁴

¹Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio, 5, I-35122 Padova, ITALY

²Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, ITALY

³Osservatorio Astronomico di Bologna, Via Zamboni 33, I-40126 Bologna, ITALY

⁴Osservatorio Astronomico di Trieste, Via G.B. Tiepolo, 11, I-34131 Trieste, ITALY

Abstract. We present atmospheric parameters for about 300 stars of different chemical composition, whose spectra will be used to study the galactic enrichment of Fe and light elements. These parameters were derived using an homogenous iterative procedure, which considers new calibrations of colour- T_{eff} relations for F, G and K-type stars based on Infrared Flux Method (IRFM) and interferometric diameters for population I stars, and the Kurucz (1992) model atmospheres. We found that these calibrations yield a self-consistent set of atmospheric parameters for $T_{\text{eff}} > 4400$ K, representing a clear improvement over results obtained with older model atmospheres. Using this T_{eff} -scale and Fe equilibrium of ionization, we obtained very low gravities (implying luminosities incompatible with that expected for RGB stars) for metal-poor stars cooler than 4400 K; this might be due either to a moderate Fe overionization (expected from statistical equilibrium calculations) or to inadequacy of Kurucz models to describe the atmospheres of very cool giants. Our T_{eff} scale is compared with other scales recently used for metal-poor stars; it agrees well with those obtained using Kurucz (1992) models, but it gives much larger T_{eff} 's than those obtained using OSMARCS models (Edvardsson et al. 1993). This difference is attributed to the different treatment of convection in the two sets of models. For the Sun, the Kurucz (1992) model appears to be preferable to the OSMARCS ones because it better predicts the solar limb darkening; furthermore, we find that our photometric T_{eff} 's for metal-poor stars agree well with both direct estimates based on the IRFM, and with T_{eff} 's derived from H α wings when using Kurucz models.

Key words: Stars: fundamental parameters - Stars: atmospheres - Stars: abundances - Stars: population II

1. Introduction

The determination of elemental abundances in metal-poor stars is a basic constraint for models of the chemical evolution of our Galaxy, and provide wealth of data about the history of star formation (see e.g. Wheeler et al. 1989). A very important rôle is played by C, N, O, Na, Mg, and Fe, which are amongst the most abundant elements, likely produced in a variety of astronomical sites. The determination of accurate abundances for these elements in a large sample of stars of different metallicities, and their discussion within the framework of galactic evolution is the main purpose of the present series of papers. In the course of this investigation, we found it necessary to discuss a number of important, related issues in order to obtain more reliable results: some of them (e.g. the solar abundances and the applicability of the adopted model atmospheres in abundance analyses) were treated in a parallel study of the spectra of RR Lyrae stars at minimum light (Clementini et al. 1995), and in more depth by Castelli and Gratton (1996). The present paper is devoted to the presentation of the adopted atmospheric parameters; these were obtained using an iterative procedure which exploits both photometric and spectroscopic data. The most relevant feature is a new, hopefully improved calibration of colours against effective temperatures (T_{eff} 's). In other papers of this series (and with the contribution of other authors) we will present a discussion of non-LTE effects, using specially devoted statistical equilibrium computations and a new empirical calibration of the collisional cross-sections, and a discussion of the adopted abundance indices and of the derived abundances within the framework of models of the galactic chemical evolution.

The colour- T_{eff} calibrations are by themselves a very interesting output of the present investigation: they have an important impact on a broad class of topics, including e.g. abundance analyses and comparisons between theoretical isochrones and cluster colour-magnitude (c-m) di-

agrams. Our new T_{eff} scale is close to that determined by King (1993: hereinafter K93); it is based on empirical determinations for population I stars, applying corrections for non-solar metallicities drawn from the same Kurucz (1992) model atmospheres used in the analysis. A quite extensive discussion of this T_{eff} scale is given in Sect. 5; we conclude that it gives reliable and consistent results for $T_{\text{eff}} > 4600$ K, while either the T_{eff} scale or the same Kurucz models seem inadequate for stars cooler than 4400 K.

2. Program stars

Before discussing the derivation of the atmospheric parameters adopted in our analysis, a short presentation of the observational data used in this series of papers is required. The original material consists in about 400 high resolution ($R \sim 50,000$), high S/N (> 150) spectra of 19 metal-poor stars acquired with the Short Camera of the Coudé Echelle Spectrograph (CES) at the ESO Coudé Auxiliary Telescope, La Silla, and with the Coudé Spectrograph at the 2.7 m telescope of the McDonald Observatory. The stellar sample is the same used by Gratton & Sneden (1991, 1994: hereinafter GS1 and GS2) in order to derive abundances of Fe-group and n -rich elements. However, the initial observations were carried out during ESO test time, kindly made available by Dr S. D'Odorico: the available observing time forced us to concentrate on the brightest ($V \leq 8$) southern metal-poor stars accessible during the observing run. This sample included only 19 stars; furthermore, all extremely metal-poor stars are giants, with the only exception of the subgiant HD 140283. This sample is too small for the present purposes and important biases are present. For this reason, we decided to increase it by adding data (equivalent widths EW) from a number of literature sources, reanalyzing them in the most homogeneous way possible: these additional data allow to better understand the selection biases present in our data, and to obtain a sample large enough for a statistically significant analysis of the results.

The additional sources of EW s were selected from papers based on high resolution, high S/N observational material; we only considered studies giving EW s for both Fe I and Fe II lines, since we used the Fe equilibrium of ionization to derive gravities: for this reason, only papers dealing with data having a rather large wavelength coverage were considered. The following works were then considered:

1. Tomkin et al. (1992: hereinafter TLLS): analysis of high excitation C and O permitted lines in 34 unevolved metal-poor stars;
2. Sneden et al. (1991) and Kraft et al. (1992) (hereinafter collectively SKPL): abundances of O from forbidden lines and Na from the doublet at 6154-60 Å in 27 field halo giants.
3. Edvardsson et al. (1993: hereinafter E93): analysis of high excitation O, Na, and Mg lines in about 180 field dwarfs with metallicity $[\text{Fe}/\text{H}] > -1$. Their data were

integrated with EW s for high excitation C lines from Clegg et al. (1981) and Tomkin et al (1995), and forbidden O lines from Nissen & Edvardsson (1992) in a smaller number of stars.

4. Zhao & Magain (1990: hereinafter ZM90): abundances of Na and Mg in 20 metal-poor dwarfs.

Since there is some overlap amongst these different samples, on the whole, data for almost 300 stars over a wide range in luminosity and metal-abundance are considered. In the remaining part of this paper, we will discuss the derivation of the atmospheric parameters used in the analysis of all this material.

3. Derivation of atmospheric parameters

When preparing the present series of papers, the grid of model atmospheres by Kurucz (1992, hereinafter K92) became available to us¹. Since these models are able to reproduce various solar features (flux distribution, photospheric abundances, limb darkening, etc.) much better than the Bell et al. (1976; hereinafter BEGN) atmospheres, they were adopted in the present analysis. We decided to revise the whole derivation of atmospheric parameters (effective temperature T_{eff} , surface gravity $\log g$, model metal abundance $[\text{A}/\text{H}]$, and microturbulent velocity v_t) for the program stars, in order to put them on a self-consistent scale. T_{eff} 's were derived from dereddened colours using semiempirical calibrations obtained through a procedure similar to that of K93; however standard T_{eff} 's obtained by means of the IRFM (Blackwell & Shallis 1977) were taken from Blackwell & Lynas-Gray (1994: hereinafter BLG), who used new calibrations based on the K92 model atmospheres. Furthermore, corrections for gravities were also obtained empirically by interpolating among values obtained for dwarfs and giants. The adopted iterative procedure (which requires approximate initial values for $\log g$, $[\text{A}/\text{H}]$, and v_t) is as follows:

1. We first obtained empirical colour- T_{eff} 's calibrations using a compilation of T_{eff} 's derived with the IRFM for ~ 140 population I stars from the lists of BLG and Bell & Gustafsson (1989); these last T_{eff} 's were corrected to put them into the same scale of those of BLG. A first correction is required because Bell & Gustafsson derived T_{eff} 's from the IRFM using the BEGN models rather than the K92 models used here; we notice that on this respect, our calibrations represent an improvement over that of K93, who used T_{eff} 's derived from the IRFM calibrated against BEGN models (Saxner & Hammarbäck 1985). The T_{eff} 's from Bell & Gustafsson were then lowered by 122 K to put them on the same scale of those by BLG. This last correction might be due to the different ways fluxes in the IR are determined by interpolation within broadband colours. Figure 1 shows the colour- T_{eff} (IRFM)

¹ 1993 CD-ROM 13 version of Atlas 9

Table 1. Polynomial coefficients of the empirical colour- T_{eff} calibrations for population I stars (valid for $n < \text{colour} < m$). Two relations are given for giants; the first one should be preferred for stars with colours smaller than the following limits: $B - V = 1.48$, $V - R = 1.10$, $R - I = 0.94$, $J - K = 0.92$, $V - K = 3.10$, $b - y = 0.739$. The second one should be preferred for stars with colours larger than these limits. Errors are standard deviations from fits

	Class	Stars	a_0	a_1	a_2	a_3	n	m
$B - V$	III	81	8843 ± 95	-6982.5 401.7	3961.8 530.5	-980.78 206.09	0.08	1.54
$B - V$	III	22	-228 ± 93	7992.9 4281.2	-3466.5 1511.8		1.20	1.64
$B - V$	V	33	8905 ± 91	-6730.4 522.5	3173.8 903.9	-552.07 434.6	0.12	1.35
$V - R$	III	81	9245 ± 140	-8392.3 887.6	3247.6 1473.8	-85.49 722.71	0.10	1.23
$V - R$	III	22	7060 ± 77	-3879.5 476.7	1046.7 168.2		0.89	2.03
$V - R$	V	29	9065 ± 182	-8067.3 1328.0	3568.5 2605.5	-131.30 1431.50	0.07	1.17
$R - I$	III	81	8824 ± 75	-11747.6 373.9	7920.2 649.0	-1123.14 400.52	0.03	0.94
$R - I$	III	22	5932 ± 88	-3109.0 389.3	969.0 159.3		0.63	1.91
$R - I$	V	33	8764 ± 90	-11850.9 545.3	9310.1 1201.8	-2265.45 963.69	0.05	0.85
$J - K$	III	68	8553 ± 84	-10456.7 1202.7	9613.5 2233.7	-3886.47 1260.56	0.17	0.97
$J - K$	III	16	10071 ± 50	-10088.2 2073.6	3843.5 1017.7		0.85	1.22
$J - K$	V	19	9850 ± 164	-17774.9 2887.6	23374.3 6894.7	-12170.60 4901.1	0.11	0.83
$V - K$	III	78	8992 ± 43	-2887.9 78.9	556.9 44.3	-40.02 7.20	0.19	3.67
$V - K$	III	13	6733 ± 63	-1136.0 325.1	99.3 35.1		3.10	6.01
$V - K$	V	33	8890 ± 60	-2782.4 136.2	523.1 97.1	-31.79 19.10	0.29	3.32
$b - y$	III	32	8736 ± 103	-9595.6 781.4	6135.2 1738.9	-1428.90 1108.00	0.06	0.95
$b - y$	III	14	11754 ± 60	-15965.3 5430.3	8172.8 3261.7		0.70	0.96
$b - y$	V	30	8592 ± 94	-7044.5 966.8	-2200.5 2786.9	5248.20 2251.70	0.06	0.79

graphs. All colours are in the Johnson system, except the Strömgren colour index $b - y$. The most appropriate colour indices can be deduced from the dispersion of the observational data; as expected, the best index is $V - K$, followed by $b - y$. However, it should be noticed that sequences for dwarfs (luminosity class V; few stars of luminosity class IV are present in the sample) and giants (luminosity class III) are clearly separated. For any colour, we then fitted cubic polynomials ($T_{\text{eff}} = a_0 + a_1 \text{ colour} + a_2 \text{ colour}^2 + a_3 \text{ colour}^3$) through the colour- T_{eff} planes for stars of luminosity class III and V separately. Polynomial coefficients are given in Table 1.

2. We derived T_{eff} 's from each observed colour for the program stars using a cubic polynomial interpolation in the theoretical T_{eff} -colour planes. However, before doing this interpolation we transformed both theoretical T_{eff} 's and observed colours, to consider the difference between the empirical and theoretical calibrations for population I stars, and the variation of colours with metallicity. This was done in two steps: (i) By assuming that the zero-point calibrations of the various theoretical colours may be in error and the IRFM yields the right temperatures, we replaced T_{eff} 's of the K92 models with those T_{eff} 's that give the same value of the colours but using the empirical calibrations ob-

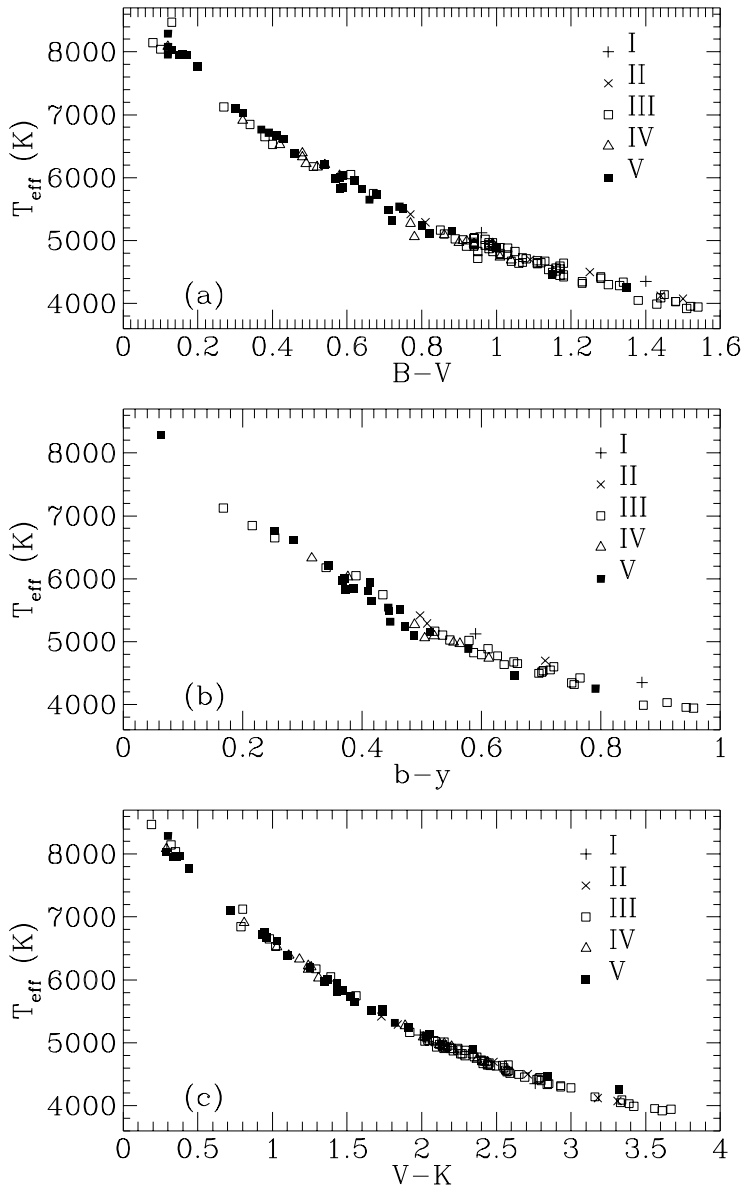


Fig. 1. Empirical relations between T_{eff} and colours for the 140 population I stars with accurate T_{eff} 's from the IRFM. Stars of different luminosity classes are marked with different symbols. For brevity, only relations for $B - V$ (panel a), $b - y$ (panel b), and $V - K$ (panel c) are shown in this figure

tained from population I stars: this coordinate transformation corresponds to the application of systematic corrections, function of T_{eff} , to the K92 temperatures, equal to the differences between the empirical and theoretical calibrations for solar metallicities. (ii) We then replaced the colours of K92 models for solar metallicity at each temperature, with the colours of K92 models for the approximate input value of the metallicity; these colours were obtained by means of a cubic polynomial interpolation through theoretical colours given by K92; this second coordinate transformation corresponds to the application of systematic correc-

tions, still a function of T_{eff} , to the observed colours to consider the individual metallicity of the star under consideration. Note that this step implies that though the K92 models may give uncorrect colours at a given temperature, they correctly predict the dependence of colours on metal abundances. This last assumption was made also by K93.

3. We applied the previous transformations separately for both giants and dwarfs; when comparing theoretical and empirical calibrations, we assumed $\log g = 4.5$ for luminosity class V; for luminosity class III, we assumed $\log g = 2$ for $T_{\text{eff}} > 4500$ K, and $\log g =$

$(T_{\text{eff}} - 3500)/500$ for $T_{\text{eff}} < 4500$ K. These values approximately match the observed $\log g$ for dwarfs and giants respectively; however, this assumption is not critical, since gravity corrections are generally small. The best temperature for each colour as function of gravity was then derived by linear interpolation/extrapolation between the values obtained for the two different logarithmic gravities, using the approximate input value for the stellar gravity.

4. We then averaged temperatures obtained from each colour, assigning weight 4 to $V - K$, 0.5 to $V - R$, and 1 to all other colours; these weights were attributed on the basis of the observed residuals about the fitting polynomials used for population I stars.
5. We used this input temperature (and the initial values of gravity, metal abundance and microturbulent velocity) to iterate the abundance analysis until (i) we had no trend of the abundances derived from individual Fe I line with expected line strength (varying v_t); (ii) the value of the model abundance was identical to the derived Fe abundance (varying $[A/H]$); and (iii) the abundances derived from Fe I and Fe II lines were the same (varying $\log g$). This abundance analysis was done using model atmospheres extracted from the grid of K92.
6. Finally, we repeated the whole procedure of temperature derivation entering the new values of gravity, metal abundance, and microturbulent velocity obtained after the previous step, and iterated this procedure until we converged to a consistent set of atmospheric parameters². No iteration was usually required when $V - K$ colours were available, since they are only weakly dependent on gravity and metallicity; one or two iterations were required for the other cases.

4. Atmospheric parameters for reanalyzed stars

For all program stars, new values for the atmospheric parameters were derived, following the iterative procedure described in Sect. 3. We used the *EW*s from the various sources cited in Sect. 2, and photometric data from Hauck & Mermilliod (1990), Schuster & Nissen (1988), Twarog & Anthony-Twarog (1994), Laird et al. (1988), Stone (1983), Pilachowski (1978), Arribas & Martinez-Roger (1987), and Alonso et al. (1994); however, only $b - y$ colours were used for E93's stars, and $b - y$ and $V - K$ colours for ZM's stars. Reddenings for stars considered in GS1 and GS2 were taken from these papers; those for the SKPL giants were taken from Twarog & Anthony-Twarog (1994), while no reddening was assumed for the dwarfs observed by TLLS, E93, and ZM90.

Since *EW*s for very few lines of Fe I were usually available from the studies of TLLS and SKPL, v_t 's were ob-

tained using a mean relation drawn from our program stars ($v_t = -0.322 \log g + 2.22 \text{ kms}^{-1}$), except for a few cases (generally very cool stars) in which obvious trends with line strength were present; based on the dispersion along this mean relation, we estimate that errors of this v_t 's are $\pm 0.3 \text{ kms}^{-1}$. For the warmer stars considered by E93, a dependence on T_{eff} must be included. We find that a good representation is given by the relation ($v_t = 1.19 \cdot 10^{-3} T_{\text{eff}} - 0.90 \log g - 2 \text{ kms}^{-1}$). We also revised the Fe I *gf*'s, to put them in a scale consistent with that adopted in this paper (see Carretta et al. 1996).

The derived atmospheric parameters are listed in Tables 2-6 (available in electronic form).

Table 2. Atmospheric parameters for stars in the original sample

Table 3. Atmospheric parameters for stars in the TLLS sample

Table 4. Atmospheric parameters for stars in the SKPL sample

Table 5. Atmospheric parameters for stars in the E93 sample

Table 6. Atmospheric parameters for stars in the ZM90 sample

5. Discussion of the adopted parameters

5.1. Kurucz 1992 and Kurucz 1995 model atmospheres

After the draft of this paper was ready, we were aware that the convective flux in Atlas 9 version used to compute the 1992 models stored on the CD-ROM 13 generated discontinuities in the grids of the colour indices for T_{eff} in the approximate range between 6700 K (for $\log g = 2$) to 8000 K (for $\log g = 4.5$). The convection formalism was improved (Castelli, 1996) and Kurucz (1995) recomputed most of the cool model atmospheres (K95 models). The 1995 models differ from the 1992 models mostly for an improved convection, for the larger number of layers (72

² Note that there is a small inconsistency here, since we used model atmospheres computed with a microturbulent velocity of 2 kms^{-1} .

rather than 64) which extend toward lower optical depths, for a better treatment of the radiation emerging from the uppermost layers, and for a few changes in some opacity routines, as that for H^- . Furthermore, all the colours are recalibrated on a different ATLAS9 Vega model (Castelli & Kurucz 1994). Rather than redoing all our lengthy computations, we directly compared colour indices and abundances from the K92 and K95 models, made recently available to us by R. Kurucz. First we considered colors, and in particular Johnson $B - V$ and $V - K$, and Strömgren $b - y$ (these are the colors having the largest weight in our T_{eff} determinations). We found small constant offsets of 0.004, 0.012 and 0.025 for $b - y$, $B - V$, and $V - K$ respectively between the original K92 colors and those we obtained using K95 models (in the sense that K95 colors are redder). These small offsets are due to slightly different assumptions about the atmospheric parameters for the reference star Vega. For the stars used in this series of papers, the theoretical T_{eff} -scale obtained using K95 models is ~ 30 K warmer. For all colors, there is a peak in the color residuals (amounting to ~ 0.02 , 0.015 , and 0.045 for $b - y$, $B - V$, and $V - K$ respectively, again K95 colors being redder) over a small range of T_{eff} (~ 6750 for $\log g = 2$, and ~ 8000 K for $\log g = 4.5$). The peak residual is smaller for metal-poor model atmospheres. Given the small T_{eff} range where these larger corrections (corresponding to 30-120 K, depending on the colour used) apply, they have negligible impact on the polynomial fitting curves used in our semiempirical procedure. Furthermore, the peaks fall outside the T_{eff} range for stars considered in this series (and in the parallel paper on RR Lyrae at minimum light by Clementini et al. 1995).

We then compared abundances obtained using K92 and K95 model atmospheres for a few typical cases, adopting in both cases the same set of atmospheric parameters. We found that K95 atmospheres yield larger abundances (by 0.008 dex) than K92 atmospheres for low excitation lines of easily ionized elements; and smaller abundances (by 0.003 dex) for high excitation lines of dominant species (like the OI IR triplet).

On the whole, we regard differences between results obtained using K92 and K95 model atmospheres as negligible with respect to other sources of error in our analysis, and in this series of papers we will keep the results obtained using K92 atmospheres.

5.2. Trends of Fe abundances with excitation potential

Use of K92 atmospheres and of the new sets of atmospheric parameters allows an homogeneous comparison to solar abundances; however, we noticed some inconsistencies, that are discussed in this section.

Dalle Ore (1992) found a systematic trends of abundances from individual Fe I lines with excitation potential for metal-poor giants, in the sense that temperature derived from line excitation is much lower than that derived

from colours (that is, a negative slope $\delta\theta$ of Fe abundances with excitation potential). We found a similar trend using star in our original sample, that admittedly included a few stars; however the large spectral coverage allowed derivation of EW s for a large set of lines having accurate laboratory gf 's. We found the following average values for the slope $\delta\theta$ in the excitation-abundance plane:

- all stars: -0.047 ± 0.009 dex/eV ($\sigma = 0.041$ dex/eV, 19 stars)
- $\log g > 4$: -0.038 ± 0.005 dex/eV ($\sigma = 0.013$ dex/eV, 6 stars)
- $3 < \log g < 4$: -0.052 ± 0.016 dex/eV ($\sigma = 0.040$ dex/eV, 6 stars)
- $\log g < 3$: -0.050 ± 0.022 dex/eV ($\sigma = 0.058$ dex/eV, 7 stars)

On the whole, the value of the slope seems to be weakly dependent on surface gravity, while the scatter seems to be a function of gravity. This suggests that either the effective temperatures of giants are ill-defined (e.g. due to errors in the estimate of reddening), or that the atmospheres of giants are somewhat different one from the other, or both. On the other side, the average slope for stars in the large sample by E93 (all with $\log g > 3$) is quite different ($\delta\theta = +0.027 \pm 0.002$, $\sigma = 0.025$, 203 independent estimates for 187 stars); a clear trend with overall metal abundance is present: $\delta\theta = (0.051 \pm 0.005)[\text{Fe}/\text{H}] + (0.040 \pm 0.021)$. However, the determinations of the slope using stars in the E93 sample are based on a few lines with solar oscillator strengths. Contamination by blending features may cause spurious trends. This point should then be reexamined using an extended line list for a large sample of stars.

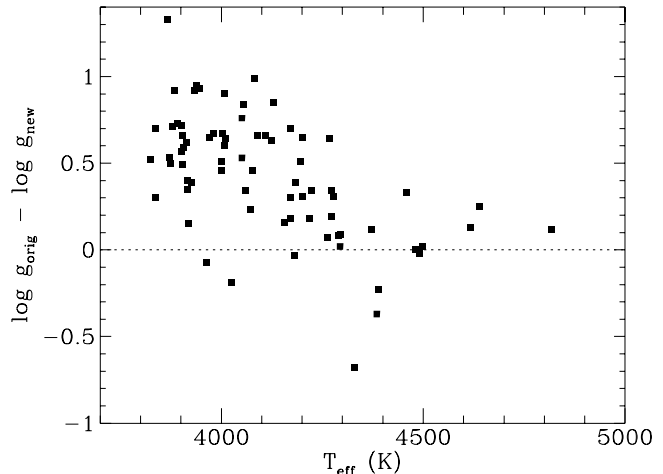


Fig. 2. Differences between gravities derived from the position in the c-m diagram ($\log g_{\text{orig}}$) and from Fe equilibrium of ionization ($\log g_{\text{new}}$) as a function of T_{eff} for the globular cluster giants considered by Carretta & Gratton (1996). A mass of $0.8 M_{\odot}$ was adopted for these stars

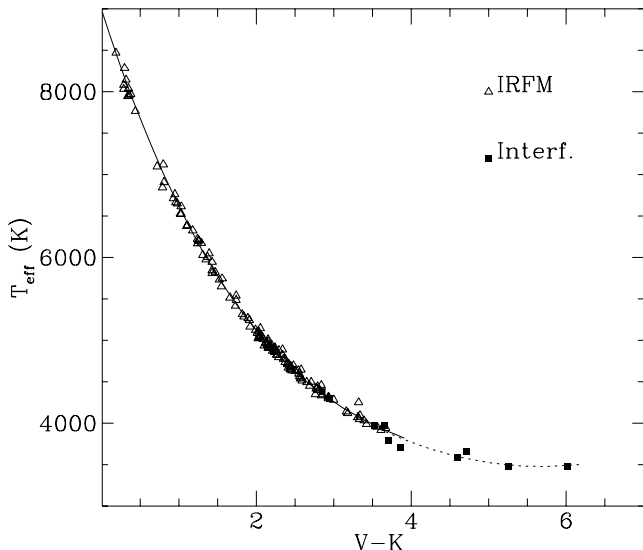


Fig. 3. Comparison between the $(V - K)$ - T_{eff} calibrations obtained using T_{eff} 's from IRFM and from diameters measured interferometrically (Di Benedetto & Rabbia 1987)

5.3. Gravities and Fe equilibrium of ionization

For another program (Carretta & Gratton 1996), we applied this same procedure to the analysis of the spectra of globular cluster giants, where gravities can be determined from luminosities, masses and effective temperatures. That analysis showed that the difference between abundances given by neutral and singly ionized lines is a function of T_{eff} . This is illustrated by the data in Fig. 2, where we plotted the differences between the gravities for globular cluster giants obtained from the procedure described in this paper, and those derived from the position in the c-m diagram, assuming a mass of $0.8 M_{\odot}$. While the agreement between the two sets of gravities is fairly good for $T_{\text{eff}} > 4600$ K, gravities derived from the Fe equilibrium of ionization are on average too low for stars cooler than 4400 K.

In the following we will consider three possible explanations for this discrepancy:

1. The IRFM cannot be reliably used for M-stars from ground-based observations alone, due to the strong molecular bands in the near-IR spectral region. It is then possible that our empirical calibration for population I stars, based on the application of the IRFM method to ground-based observations, is not accurate for the coolest stars. On the other side, T_{eff} 's for M giants can be derived from determinations of stellar angular diameters. We then tested the cool end of our T_{eff} -colour calibrations by comparing the T_{eff} 's derived using the IRFM with those that can be obtained from interferometric determinations of stellar diame-

ters (Di Benedetto & Rabbia, 1987: see Fig. 3)³. We found however an excellent agreement between the two sets of T_{eff} 's; a calibration obtained by merging the two sets differs by ≤ 20 K from that obtained using T_{eff} 's from the IRFM alone for $T_{\text{eff}} > 4000$ K.

2. Some Fe overionization is expected for the coolest, very low gravity giants. We performed an explorative statistical equilibrium computation for the coolest star in our own sample (HD 187111) using MULTI code (Scharmer & Carlsson, 1985; Carlsson 1986) and a 60-level Fe I model atom (for a full description of this model atom and the methods used in this and other statistical equilibrium computations, see Gratton et al. 1996). We parametrized the poorly known cross sections for collisions with H I atoms by matching observations of RR Lyrae at minimum light (see Clementini et al. 1995). We found that the maximum non-LTE correction to the Fe I abundance in HD 187111 compatible with the observations of RR Lyrae variables (where departures from LTE are expected to be larger than in the program stars) is 0.08 dex (abundances from Fe II lines are not influenced by departures from LTE). A smaller correction (0.04 dex) is expected for HD 136316, while non-LTE corrections to Fe abundances should be very small for the other program stars. If LTE abundances from Fe I lines for HD 187111 are corrected for this amount, we derive slightly larger surface gravities (~ 0.25 dex). This correction is about half the value required to reduce the luminosity of this metal-poor star below that expected at the tip of the red giant branch. Hence, departures from LTE are a promising candidate to explain part of the observed discrepancy.
3. We finally tested the hypothesis that the model atmospheres may be responsible for the observed discrepancies. This was done by replacing BEGN models to the K92 ones for a few typical cases. Abundances for the Sun derived from the K92 models and updated laboratory gf 's are close to those given by the Holweger & Muller (1974) model, and to the meteoritic values (Anders & Grevesse 1989), while it is well known that abundances provided by BEGN solar model are too low by $\sim 0.08 - 0.15$ dex (the exact value depends on the line list used). Furthermore, K92 model reproduces the solar flux distribution much better than the BEGN model; hence K92 models should be preferred in the analysis of solar type stars. However, for all the species investigated, the K92 and BEGN models yield stellar abundances relative to the solar ones which differ less than 0.03 dex for $T_{\text{eff}} > 4400$ K. When doing a relative analysis for cooler stars, the ionization equilibrium given by BEGN model atmospheres is in

³ We found that these determinations give a scatter much smaller than the T_{eff} 's from lunar occultations (Ridgway et al. 1980) in colour vs T_{eff} 's diagrams

better agreement with that obtained using T_{eff} 's from IRFM and gravities from the c-m diagram, although the discrepancy is not completely canceled. Gravities obtained from the equilibrium of ionization are too low when using K92 models for these cool stars. This fact suggests that K92 models are not fully adequate for the analysis of stars with $T_{\text{eff}} < 4400$ K.

Since in the present series of papers we are mainly concerned with stars with $T_{\text{eff}} > 4400$ K, we will use K92 model atmospheres; however, results for the coolest stars require further investigations: whenever possible, conclusions will only be drawn using warmer stars (preferably dwarfs).

6. Comparison between empirical calibrations and theoretical colours

Figures 4 and 5 compare the present empirical T_{eff} -colour calibrations for population I dwarfs and giants respectively with the theoretical calibrations directly based on K92 fluxes for the Johnson $B - V$, $V - R$, $R - I$, $J - K$, and $V - K$ colours, and for the Strömgren $b - y$ index. The agreement between the empirical and theoretical calibrations is very good for $V - K$; significant deviations can be noticed only at very low T_{eff} 's ($T_{\text{eff}} < 4500$ K) for dwarfs, and high T_{eff} 's ($T_{\text{eff}} > 6000$ K) for giants, where we have only a few calibrating stars. The comparison is also quite good for $B - V$, $R - I$, and $b - y$, although corrections (a few hundredths of mag) are not negligible. In particular, we notice that the $B - V$ colour for the Sun derived from our empirical calibration ($B - V = 0.62$) is 0.03 mag bluer than that provided by the theoretical calibration. Similar corrections should be applied when colours from K92 models are applied to theoretical isochrones. The comparison is poorer for the $V - R$ colour.

7. Comparisons with other T_{eff} -scales

Of particular interest is the comparison of the current T_{eff} -scale with those recently used by other authors for metal-poor stars.

7.1. Giants

7.1.1. Dalle Ore et al. (1996)

Dalle Ore et al. (1996) used the K92 models in an analysis of the chemical composition of HD 122563; their T_{eff} (4590 K) derived with the IRFM agrees very well with our value for this star (4583 K).

7.1.2. Cohen et al. (1978)

Figure 6 compares the present calibration of $V - K$ with that obtained by Cohen et al. (1978), often used in the analysis of globular cluster giants. Cohen et al. scale is based on JHK magnitudes and colours, calibrated against

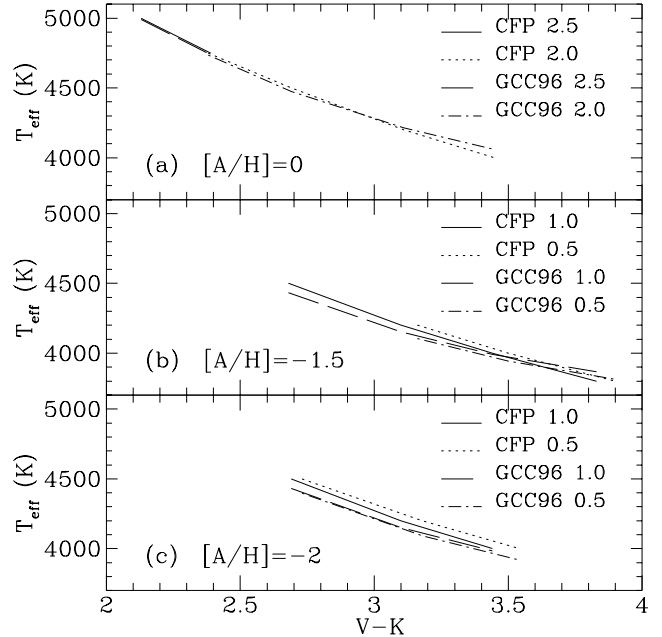


Fig. 6. Comparison between the present T_{eff} -colour calibrations for giants (GCC96) and the calibrations by Cohen et al. (1978: CFP). Panel a shows results for $[\text{Fe}/\text{H}]=0$, panel b for $[\text{Fe}/\text{H}]=-1.5$, and panel c for $[\text{Fe}/\text{H}]=-2$. Different line types are used for models with different values of $\log g$

the old Kurucz (1979) model atmospheres: it predicts that $V - K$ colours are independent of gravity and metal abundance. The three panels of Fig. 6 compare the two scales in different abundance regimes and for different values of gravities. While the overall comparison is fairly good, the metallicity dependence is different in the two cases, since we are using the K92 models. Furthermore, the gravity dependence at low T_{eff} 's and metallicity seems not negligible; however, it is now clear that K92 models are not fully adequate in the analysis of the coolest, very metal-poor giants.

7.1.3. Clementini et al. (1995)

It is useful to compare our T_{eff} scale with that adopted by Clementini et al. (1995), since results of the abundance analysis in that paper will be used in the second paper of this series to calibrate our own statistical equilibrium computations. Figure 7 compares the two empirical calibrations of the $V - K$ index: the relations are virtually identical in the typical temperature range for RR Lyrae at minimum light (6000-6300 K).

7.1.4. Blackwell & Lynas Gray (1994)

The comparison between the T_{eff} scale of this paper and that of BLG is shown in Fig. 8: the agreement is excellent, but the range of validity of the BLG scale is smaller than the present scale.

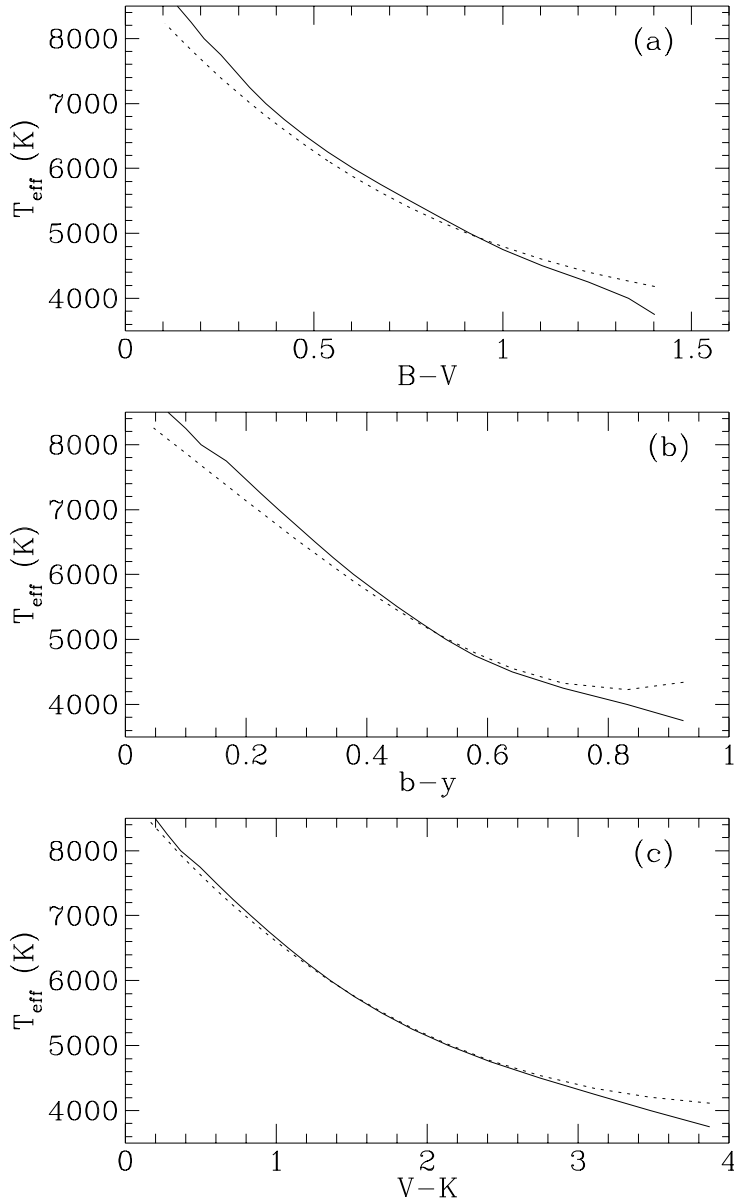


Fig. 4. Comparison between the present empirical T_{eff} -colour calibrations for population I dwarfs (dashed line) and the theoretical calibrations directly based on K92 fluxes (Kurucz 1992) (solid line) for various colours. For brevity, only the comparisons for $B - V$ (panel a), $b - y$ (panel b), and $V - K$ (panel c) are shown in this figure

7.2. Dwarfs

7.2.1. King (1993)

More intriguing is the situation for metal-poor dwarfs. The present T_{eff} scale agrees fairly well with that of K93, as shown by the comparisons of Fig. 9; this is not surprising, since they were derived using the same model atmospheres and a similar procedure.

7.2.2. Edvardsson et al. (1993)

Recently, E93 published the results of the analysis of a very extensive spectroscopic survey of field dwarfs. All stars considered by E93 have $[\text{Fe}/\text{H}] > -1$; however, Nissen et al. (1994) presented the results of the analysis of a few more metal-poor dwarfs whose atmospheric parameters were derived with a similar technique. A star-to-star comparison between our and E93 and Nissen et al. sets of atmospheric parameters shows large discrepancies in the adopted T_{eff} 's for a few stars. This effect is systematic, as shown by Fig. 10, which displays the difference between

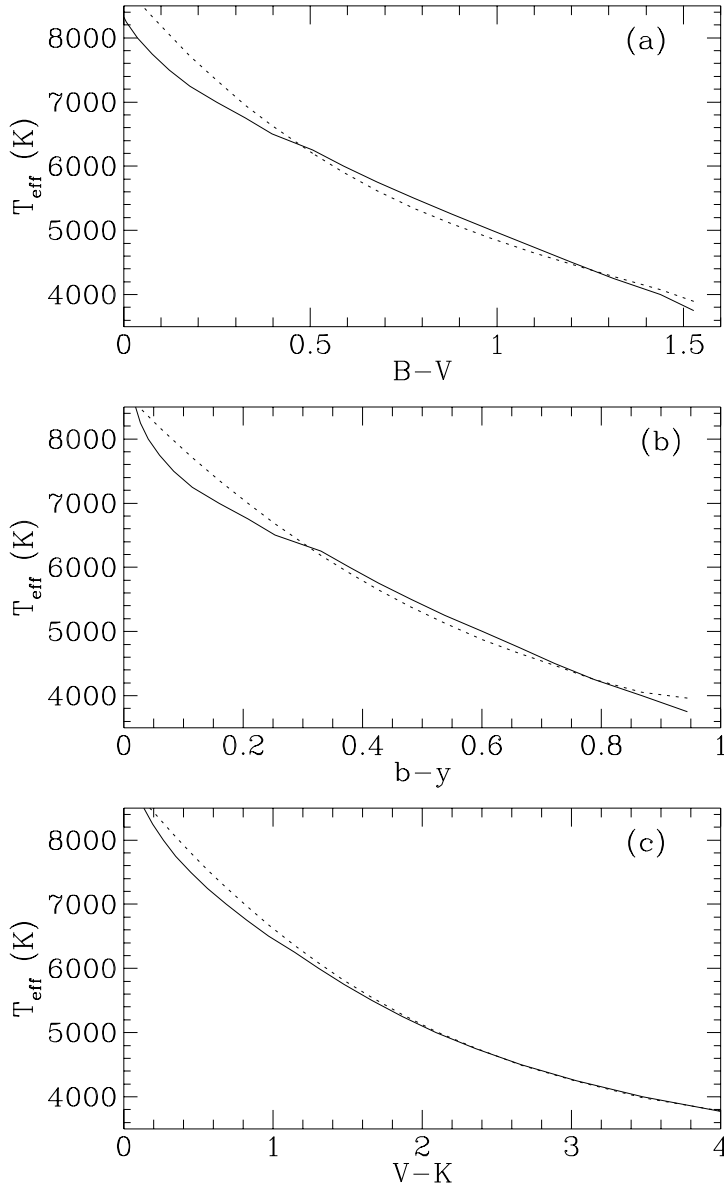


Fig. 5. The same as Fig. 4 but for population I giants

the T_{eff} 's derived by the two techniques for the stars observed by E93 and Nissen et al. against $[\text{Fe}/\text{H}]$. The best fit regression line with $[\text{Fe}/\text{H}]$ is:

$$\Delta T_{\text{eff}} = -(174.9 \pm 7.5)[\text{Fe}/\text{H}] - (81 \pm 30), \quad (1)$$

based on 187 stars. The Persson linear regression coefficient is $r^2 = 0.746$, but there are minor, not negligible correlations with gravity and T_{eff} ; the regression using all three variables is:

$$\begin{aligned} \Delta T_{\text{eff}} = & (-171.5 \pm 7.2)[\text{Fe}/\text{H}] - (45 \pm 14) \log g \\ & - (0.0492 \pm 0.0074)T_{\text{eff}} + (405 \pm 27), \end{aligned}$$

with $r^2 = 0.798$, a marginal but significant improvement. This comparison shows that T_{eff} 's may be different

by as much as ~ 400 K for the most metal-poor stars, even though the same colours are used; this is an enormous difference causing discrepancies as large as $0.4 \div 0.5$ dex in the derived $[\text{Fe}/\text{H}]$. A small part of this discrepancy can be attributed to the rather large values of reddening $E(b-y)$ adopted by Nissen et al. (1994), and for individual stars there are colour indices yielding slightly different T_{eff} 's using our prescriptions. However most of this discrepancy is real, and at *prima facie* surprising, since both T_{eff} scales are linked to accurately determined T_{eff} 's for Population I stars, for which a good agreement exists among determinations by different authors. However, a major difference is the use of different grids of model atmospheres: E93 and Nissen et al. used the new (unpublished) OSMARCS

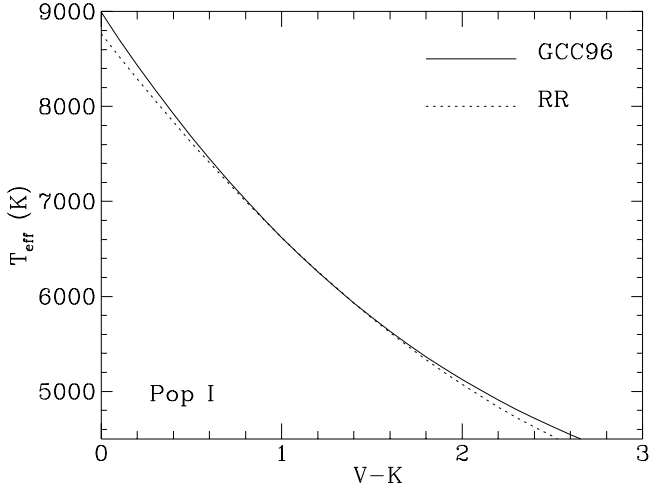


Fig. 7. Comparison between the T_{eff} scale of this paper (GCC96) and that of Clementini et al. (1995: RR) for population I dwarfs

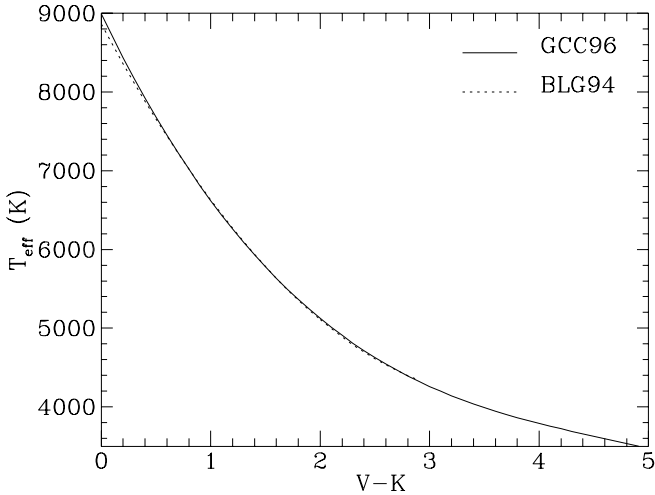


Fig. 8. Comparison between the T_{eff} scale of this paper (GCC96) and that of BLG; the agreement is excellent, but the range of validity of the BLG scale is smaller than the present scale

model atmospheres, while we used the K92 ones. Even though these two sets of atmospheric models use very similar line opacities, they differ in the treatment of convection, since K92 models include some overshooting, which is not present in OSMARCS atmospheres. This causes different $T(\tau)$ relations, as shown in Fig. 11 for both the Sun and a metal-poor dwarf atmospheres; the K92 models have a bump at $\log \tau \sim 0$, which is not present in OSMARCS models. In metal-rich atmospheres, this bump is at rather large optical depths, and it does not affect significantly the stellar colours. Instead, the bump is at shallower optical depths in the more transparent atmospheres of metal-poor

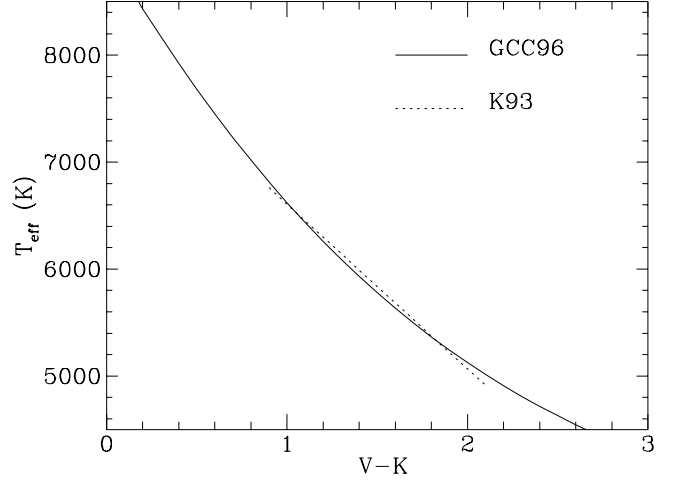


Fig. 9. Comparison between the T_{eff} scale of this paper (GCC96) and K93 for population I dwarfs

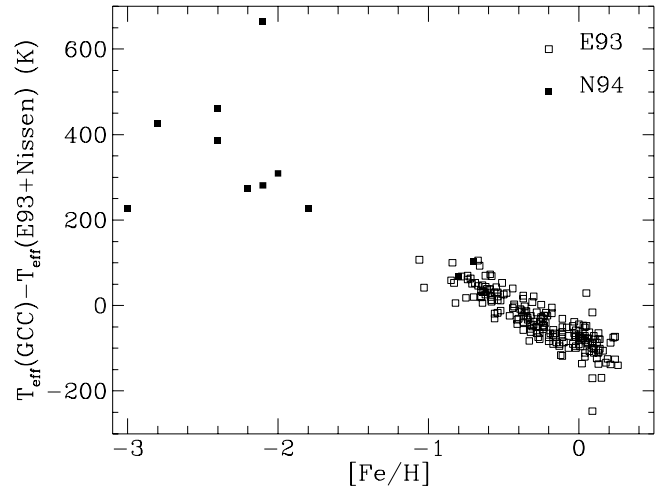


Fig. 10. Plot of the differences between original T_{eff} 's for stars in the Edvardsson et al. (1993) and Nissen et al. (1994) samples and those derived using our calibration, as a function of our value for $[\text{Fe}/\text{H}]$

stars; the consequence is that the two models predict a very different dependence of colours on metal abundance: e.g. at $b-y = 0.35$, OSMARCS models with $[\text{Fe}/\text{H}] = 0$ are ~ 210 K warmer than models with $[\text{Fe}/\text{H}] = -1$, while the analogous difference for the K92 models is only ~ 40 K. The discrepancy between the two grids is smaller for low T_{eff} stars, but these are not included in the E93 and Nissen et al. papers.

The most sensitive test for model atmospheres is the comparison between predicted and observed solar limb-darkening relations. Blackwell, Lynas-Gray and Smith (1995) show that this comparison clearly favors the K92 model atmospheres with respect to the OSMARCS

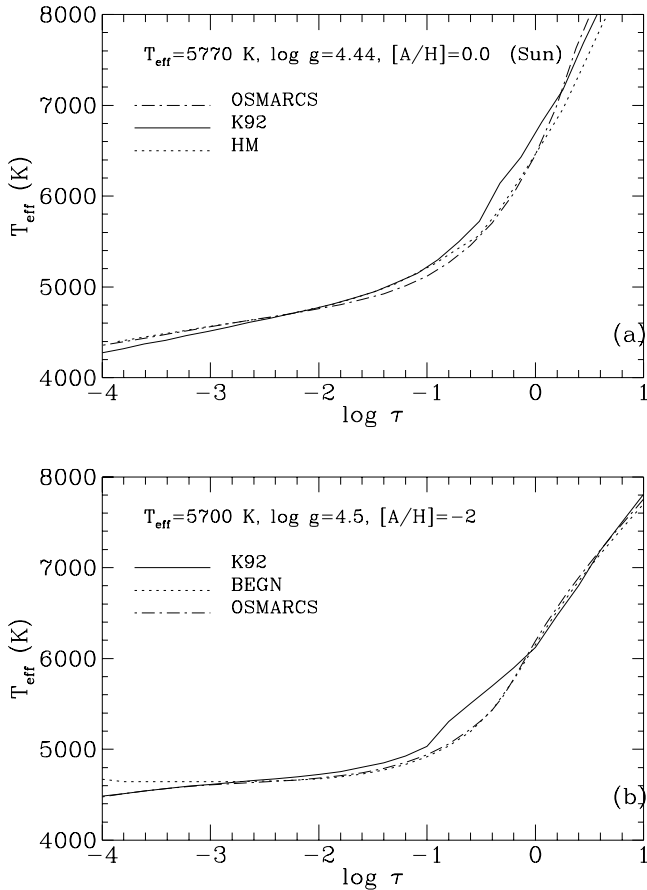


Fig. 11. $T(\tau)$ relations for the Sun (panel a) and a metal-poor dwarf (panel b) using different model atmospheres: K92 (solid line), OSMARCS (dot dashed line), Holweger & Müller (1974: HM, dotted line in panel a), and BEGN (dotted line in panel b)

ones; similar results were also obtained independently by Castelli and Gratton (1996) and Edvardsson (private communication). This fact suggests that at least in the solar atmosphere convection transports energy more efficiently around unity optical depth than the mixing-length theory predicts. This may be a consequence of neglecting the inhomogeneities observed in the solar atmosphere. The larger freedom given by the addition of a new parameter (related to overshooting) allows a better representation of the temperature structure of the solar atmosphere in K92 models. Since it is not entirely clear that this also applies to atmospheres different from that of the Sun (see e.g. Castelli and Gratton 1996), in the next two subsections we will further investigate the consistency of the present scale, by comparing our T_{eff} 's with those obtained by directly using the IRFM for metal-poor dwarfs, and the model predictions with observed profiles of the Balmer lines. We found a good internal consistency in results obtained with the K92 models.

7.2.3. T_{eff} 's from IRFM for subdwarfs

Magain (1987) derived T_{eff} 's for eleven metal-poor dwarfs using the IRFM and the BEGN model atmospheres; it must however be noticed that his T_{eff} 's derived from J and K magnitudes are quite different (those derived from J being lower by 131 ± 12 K on average). His T_{eff} -scale is lower than ours by ~ 140 K, with no trend with metal abundance; this difference is equal to the difference between the T_{eff} -scale of Magain and that of Saxner & Hammarbäck (1985) at $[\text{Fe}/\text{H}] = -0.5$, the lower edge of validity of this last scale (see also K93). However, to make a meaningful comparison, Magain's T_{eff} 's should be corrected for the systematic differences between T_{eff} 's derived using the IRFM with BEGN and K92 model atmospheres. These have been computed only for population I stars (BLG; Mégessier 1994); if these corrections are applied, Magain's T_{eff} 's are increased by 90 K on average (the correction is rather large for T_{eff} 's derived from J magnitudes, while it is quite small for those obtained from K). The mean difference with the current T_{eff} -scale is then reduced to 46 ± 14 K. Furthermore, T_{eff} 's derived from J and K magnitudes would now be in fair agreement with each other, the mean difference being reduced to 21 ± 12 K. This test should be repeated with values for the R ratio of the IRFM appropriate for metal-poor stars: however, these early results suggest that the dependence of colours on metal abundance given by K92 models should not be far from correct.

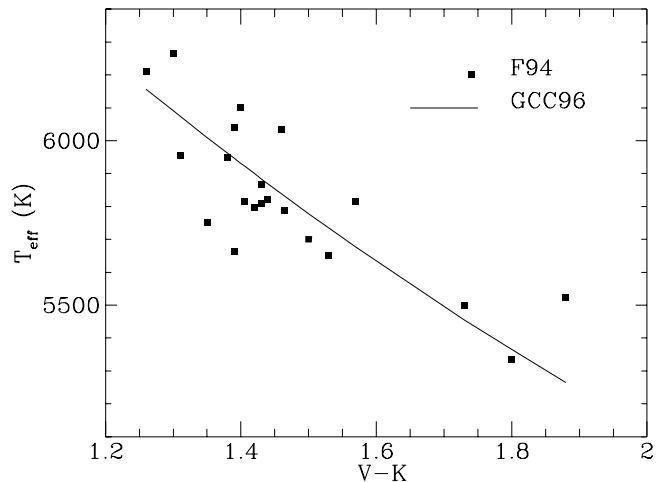


Fig. 12. Comparison of our T_{eff} calibration (GCC96) with T_{eff} 's deduced from the wing of Balmer lines (Fuhrmann et al. 1993, 1994: F94) for some metal-poor dwarfs

7.2.4. T_{eff} 's from Balmer line profiles for subdwarfs

While the far wings of H_{α} are quite independent from gravity, metallicity and convection of the model atmo-

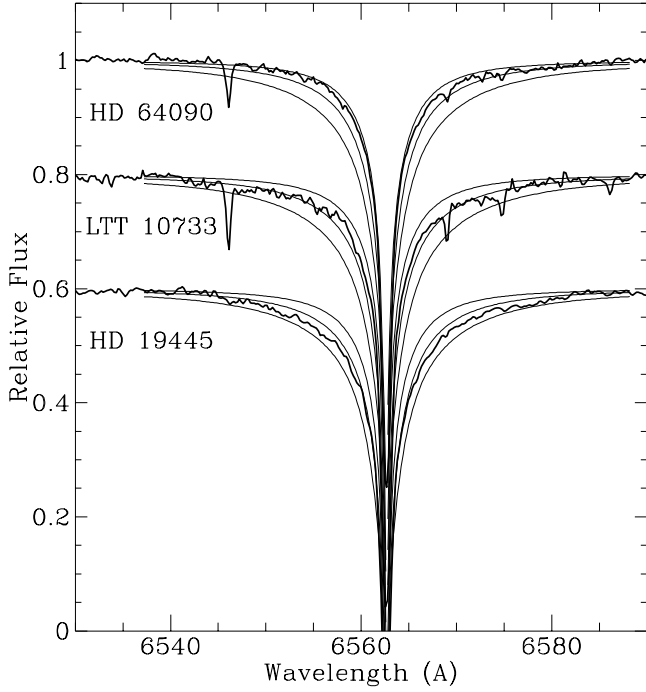


Fig. 13. Comparison between observed H_α profiles for three subdwarfs (HD 64090, LTT 10733, and HD 19445) and synthetic profiles computed with $T_{\text{eff}} = 5500, 6000$, and 6500 K. In these computations, the metal abundances were set at $[A/H] = -1$ for LTT10733, and $[A/H] = -2$ for the two other stars

Table 7. T_{eff} 's from H_α for seven subdwarfs

Star	$(V - K)$	$[\text{Fe}/H]_{\text{SN}}$	$T_{\text{eff}} (V - K)$	$T_{\text{eff}} (H_\alpha)$
HD 19445	1.37	-1.91	6112	6250
HD 64090	1.72	-1.69	5510	5500
HD114762	1.41	-0.87	5964	5750
HD194598	1.35	-1.11	6077	6100
HD201891	1.39	-1.08	6009	6000
LTT10733	1.525	-1.04	5788	5900
LTT11819	1.79	-1.56	5406	5400

spheres (and are then good temperature indicators for solar type stars), those of the other Balmer lines are strongly dependent on how convection is handled when computing model atmospheres, due to its effect on the temperature stratification of the model. Fuhrmann et al. (1993) employed this dependence to determine the best value for the pressure scale height in the mixing length formalism, to be used when modelling atmospheres for metal-poor dwarfs. Unfortunately, they used the old Kurucz (1979) model atmospheres, and their results cannot be directly used in the present context. We note, however, that our

T_{eff} -scale compares quite well with the T_{eff} 's determined by Fuhrmann et al. (1994; see Fig. 12).

For another program, we acquired spectra of several subdwarfs at a resolving power of $\sim 15,000$ and $S/N \sim 250$ using the REOSC Echelle spectrograph at the 182 cm Copernicus reflector of Asiago Observatory. This spectrograph uses a 79 gr/mm echelle grating and a large format front illuminated Thomson CCD detector, with no appreciable diffraction fringes. These spectra are then quite well suited for the determination of T_{eff} 's from the H_α profiles. Preliminary reduced spectra for seven subdwarfs were used by Clementini et al. (1995) to derive T_{eff} 's from H_α profiles using K92 model atmospheres. Details about data reduction are given in Clementini et al.: here we only remind that particular care was devoted to flat fielding and subtraction of the telluric lines. For two stars (HD 19445 and HD 114762) we could directly compare the H_α profiles derived from our spectra with those by Fuhrmann et al. The agreement is excellent: profiles from the two sources agree within $\sim 0.5\%$.

The observed H_α profiles were compared with synthetic profiles computed using K92 models and our own spectral synthesis code, which included Doppler, natural damping, resonance (Ali & Griem 1965, 1966), and Stark (Vidal et al. 1970) broadening, following prescriptions similar to those adopted by Fuhrmann et al. (1993, 1994). These prescriptions should be correct for electron densities above 10^{11} electrons per cm^3 , that is throughout most of dwarf atmospheres. However, line formation in the outer part of the atmospheres may be affected by appreciable deviations from LTE: hence these part of the profiles (as well as those contaminated by other lines) were not considered in the T_{eff} derivations. A comparison with the solar flux spectrum (Kurucz et al. 1984) showed that our computed profiles with the K92 model atmospheres reproduce observations very well (incidentally, good agreement is also obtained when using the OSMARCS and Holweger & Müller, 1974, atmospheres).

A comparison of observed and computed profiles for three stars is given in Fig. 13. Our T_{eff} 's from H_α profiles for the seven subdwarfs are listed in Table 7, where metal abundances are from Schuster & Nissen (1989)⁴. In this table we also give T_{eff} 's from our photometric calibrations (averaging $V - K$ colors from Alonso et al. (1994) and Laird et al. (1988), both transformed into the Johnson system using the relations given by Alonso et al. 1994). The agreement between T_{eff} 's derived from spectroscopy

⁴ T_{eff} 's presently derived from H_α wings are slightly different from both those obtained in Clementini et al (1995) and Castelli and Gratton (1996). These small differences with Clementini et al. are due to the improvement of our code, the differences with Castelli and Gratton are due to the use made by them of the BALMER9 and SYNTH codes from Kurucz. The difference between the code used in this paper and the Kurucz codes are mostly due to the way how the transfer equation is solved.

and photometry is excellent: the mean difference is 6 ± 43 . The r.m.s. scatter of star-to-star residuals (114 K) indicate that internal errors are ~ 100 K; we attribute these errors to small ($\sim 1\%$) uncertainties in the location of the continuum level. We conclude that the comparison with H_α profiles supports our colour-temperature calibrations.

8. Comparison with parameters used in the original analyses

8.1. GS1 and GS2

The new temperatures and gravities are larger for dwarfs and smaller for giants with respect to the values used in GS1 and GS2. Metal abundances and microturbulent velocities are also larger for dwarfs, while they are close to the old values for giants. We computed linear regression fits through the residuals between new and old values of the atmospheric parameters as a function of surface gravity; the relations are as follows:

$$T_{\text{eff,us}} - T_{\text{eff,old}} = (45.7 \pm 6.1) \log g_{\text{us}} - (100 \pm 41) \text{ K}$$

$$\log g_{\text{us}} - \log g_{\text{old}} = (0.147 \pm 0.027) \log g_{\text{us}} - (0.35 \pm 0.18)$$

$$v_{\text{t,us}} - v_{\text{t,old}} = 0.088 \pm 0.049 \log g_{\text{us}} - (0.23 \pm 0.32) \text{ km/s}$$

$$[\text{Fe}/\text{H}]_{\text{us}} - [\text{Fe}/\text{H}]_{\text{old}} = (0.046 \pm 0.011) \log g_{\text{us}} + (0.101 \pm 0.076)$$

We notice that the main conclusions of the present series of papers are not influenced by these variations of the atmospheric parameters, although abundances for individual stars may be different by as much as 0.3 dex.

8.2. TLLS

These atmospheric parameters are rather different from the original ones; on average, our T_{eff} 's are larger than those found in TLLS by 165 ± 16 K, the $\log g$'s by 0.31 ± 0.03 , the $[\text{Fe}/\text{H}]$'s by 0.29 ± 0.02 , while the v_{t} 's are smaller by $0.67 \pm 0.03 \text{ km s}^{-1}$. We found no significant trend for these offsets with T_{eff} , $\log g$, and $[\text{Fe}/\text{H}]$, except of course for v_{t} .

8.3. SKPL

Differences with SKPL are much smaller (on average differences in the sense us-SKPL are -78 ± 18 K, -0.24 ± 0.07 dex, 0.02 ± 0.02 dex, and $-0.12 \pm 0.03 \text{ km s}^{-1}$ for T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$ and v_{t} respectively), but there are trends with T_{eff} .

8.4. E93

Significative trends with metal abundances are present when we compare our adopted parameters for the stars considered by E93 with those adopted in their preliminary analysis:

$$T_{\text{eff,us}} - T_{\text{eff,E93}} = -(180 \pm 9)[\text{Fe}/\text{H}]_{\text{us}} - (81 \pm 35) \text{ K},$$

$$\log g_{\text{us}} - \log g_{\text{E93}} = -(0.31 \pm 0.04)[\text{Fe}/\text{H}]_{\text{us}} - (0.11 \pm 0.17) \text{ dex},$$

$$[\text{Fe}/\text{H}]_{\text{us}} - [\text{Fe}/\text{H}]_{\text{E93}} = -(0.165 \pm 0.008)[\text{Fe}/\text{H}]_{\text{us}} - (0.024 \pm 0.045) \text{ dex}.$$

These trends may be explained by the differences in the T_{eff} scales (see Sect. 7.2.2).

8.5. ZM90

No trend with metallicity is present when we compare our parameters with those originally adopted by ZM90. Mean differences (20 stars) are:

$$T_{\text{eff,us}} - T_{\text{eff,ZM90}} = 137 \pm 4 \text{ K},$$

$$\log g_{\text{us}} - \log g_{\text{ZM90}} = 0.65 \pm 0.02 \text{ dex},$$

$$[\text{Fe}/\text{H}]_{\text{us}} - [\text{Fe}/\text{H}]_{\text{ZM90}} = 0.30 \pm 0.01 \text{ dex},$$

with standard deviations of 20 K, 0.09 dex, and 0.03 dex respectively. The temperature difference corresponds to the use of the calibration by Magain (1987) by ZM90.

9. Conclusions

We have presented a new, self-consistent set of atmospheric parameters for about 300 metal-poor stars, that will be analyzed for the abundances of Fe and light elements (C, N, O, Na, and Mg) in forthcoming papers of this series. The most important aspect of this derivation is the determination of a new T_{eff} scale, based on the K92 model atmospheres. Our T_{eff} scale is based on T_{eff} 's determined empirically using the IRFM for about 140 population I stars. We considered separately dwarfs and giants, so that T_{eff} 's for stars of any gravity can be derived by interpolation/extrapolations. Cubic polynomials drawn through the observational points allows to correct theoretical T_{eff} 's from the K92 models: T_{eff} 's appropriate for any star can then be obtained by an iterative procedure by using the theoretical dependence of colours on

metal abundance, once abundance determined from the line analysis and gravities given by Fe equilibrium of ionization are known.

A discussion of our T_{eff} scale shows that it gives consistent results for stars with $T_{\text{eff}} > 4500$ K, while gravities determined from the equilibrium of ionization for Fe are too low for giants cooler than this limit. We discuss several possible causes of this discrepancy: we found that departures from LTE may explain part of it. However, K92 models are likely not adequate matches to the atmospheres of the coolest metal-poor giants.

We compared our T_{eff} scale with others from the literature. We found excellent agreement with other T_{eff} scales based on the K92 model atmospheres (in particular, the agreement is good with K93 T_{eff} 's), while there is a serious discrepancy with the T_{eff} 's determined for metal-poor dwarfs using the new OSMARCS models. We attribute this discrepancy to the different way convection is handled in the two set of models. K92 model atmospheres better reproduces the solar limb darkening than the OSMARCS models. We find that additional confirmations of the present T_{eff} scale for metal-poor dwarfs are provided by independent determinations of T_{eff} 's obtained by both the IRFM and the wings of H_{α} .

Acknowledgements. We are much thankful to Dr M. Carlsson, who provided a copy of MULTI code and kindly advised us on its use; to Dr R. Kurucz, who provided tapes containing his huge line list, and model atmospheres in advance of publication; and to the referee (dr B. Edvardsson) for his careful reading and stimulating suggestions. This research has made use of the Simbad database, operated at CDS, Strasbourg, France.

References

- Ali, A.W., Griem, H.R. 1965, Phys. Rev., 140, 1044
 Ali, A.W., Griem, H.R. 1966, Phys. Rev., 144, 366
 Alonso, A., Arribas, S., Martinez-Roger, C. 1994, A&AS, 107, 365
 Anders, E., Grevesse, N. 1989, Geochem. Cosmochem. Acta, 53, 197
 Arribas, S., Martinez-Roger, C. 1987, A&AS, 70, 303
 Bell, R.A., Gustafsson, B. 1989, MNRAS, 236, 653
 Bell, R.A., Eriksson, K., Gustafsson, B., Nordlund, Å. 1976, A&AS, 23, 37 (BEGN)
 Blackwell, D.E., Lynas-Gray, A.E. 1994, A&A, 282, 899 (BLG)
 Blackwell, D.E., Shallis, M.J. 1977, MNRAS, 180, 177
 Blackwell, D.E., Lynas-Gray, A.E., Smith, G. 1995, A&A, 296, 217
 Carlsson, M. 1986, Uppsala Astron. Obs. Rep. 33
 Carretta, E., Gratton, R.G. 1996, in preparation
 Carretta, E., Gratton, R.G., Sneden, C. 1996, in preparation
 Castelli, F., 1996, in Model Atmospheres and Spectrum Synthesis, PASPCS, in press
 Castelli, F., Gratton, R.G. 1996, in preparation
 Castelli, F., Kurucz, R.L. 1994, A&A, 281, 817
 Clegg, R.E.S., Lambert, D.L., Tomkin, J. 1981, ApJ, 250, 262
 Clementini, G., Carretta, E., Gratton, R.G., Merighi, R., Mould, J., McCarthy, J.K. 1995, AJ, 110, 2319
 Cohen, J.G., Frogel, J.A., Persson, S.E. 1978, ApJ, 222, 165
 Dalle Ore, C. 1992, Ph. D. Thesis, Un. California at Santa Cruz
 Dalle Ore, C., Gratton, R.G., Peterson, R.C. 1996, in preparation
 Di Benedetto, G.P., Rabbia, Y. 1987, A&A, 188, 114
 Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E., Tomkin, J. 1993, A&A, 275, 101 (E93)
 Fuhrmann, K., Axer, M., Gehren, T. 1993 A&A, 271, 451
 Fuhrmann, K., Axer, M., Gehren, T. 1994 A&A, 285, 585
 Gratton, R.G., Sneden, C. 1991, A&A, 241, 501 (GS1)
 Gratton, R.G., Sneden, C. 1994, A&A, 287, 927 (GS2)
 Gratton, R.G., Carretta, E., Gustafsson, B., Eriksson, K. 1996, in preparation
 Hauck, B., Mermilliod, M. 1990, A&AS, 86, 107
 Holweger, H., Müller, E.A. 1974, Solar Phys., 39, 19
 King, J.R. 1993, AJ, 106, 1206 (K93)
 Kraft, R.P., Sneden, C., Langer, G.E., Prosser, C.F. 1992, AJ, 104, 645
 Kurucz, R.L. 1979, ApJS, 40, 1
 Kurucz, R.L. 1992, private communication (K92)
 Kurucz, R.L. 1995, private communication (K95)
 Kurucz, R.L., Furenlid, I., Brault, J., Testerman, L. 1984, Solar Flux Atlas from 296 to 1300 nm (Harvard, Cambridge)
 Laird, J.B., Carney, B.W., Latham, D.W. 1988, AJ, 95, 1843
 Magain, P. 1987, A&A, 179, 176
 Mégessier, C. 1994, A&A, 289, 202
 Nissen, P.E., Edvardsson, B. 1992, A&A, 261, 255
 Nissen, P.E., Gustafsson, B., Edvardsson, B., Gilmore G. 1994, A&A, 285, 440
 Pilachowski, C.A. 1978, PASP, 90, 675
 Ridgway, S.T., Jacoby, G.H., Joyce, R.R., Siegel, M.J., Wells, D.C. 1980, ApJ, 235, 126
 Saxner, M., Hammarbäck, G. 1985, A&A, 151, 372
 Scharmer, G.B., Carlsson, M. 1985, J. Comput. Phys., 59, 56
 Schuster, W.J., Nissen, P.E. 1988, A&AS, 73, 225
 Schuster, W.J., Nissen, P.E. 1989, A&A, 222, 69
 Sneden, C., Kraft, R.P., Prosser, C., Langer, G.E. 1991, AJ, 102, 2001 (SKPL)
 Stone, R.P.S. 1983, PASP, 95, 27
 Tomkin, J., Lemke, M., Lambert, D.L., Sneden, C. 1992, AJ, 104, 1568 (TLLS)
 Tomkin, J., Woolf, V.M., Lambert, D.L., Lemke, M. 1995, AJ, 109, 2204
 Twarog, B., Anthony-Twarog, B. 1994, AJ, 107, 1577
 Vidal, C.R., Cooper, J., Smith, E.W. 1970, JQSRT, 10, 1011
 Wheeler, J.C., Sneden, C., Truran, J.W. 1989, ARAA, 27, 279
 Zhao, G., Magain, P. 1990, A&A, 238, 242